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5 Impact of Pesticides on Ground Water Contamination

Robert F. Carsel and Charles N. Smith

More than 20 years ago Rachel Carson focused public attention on the potential effects of pesticides on the environment. Her book, *Silent Spring*, dramatically portrayed the results of environmental contamination by pesticides on the global ecosystem. *Silent Spring* brought the use of pesticides and their effects on surface waters and populations of nontarget organisms into public view. Even the term "ground water" was virtually unknown to the general public when *Silent Spring* was written. Carson also identified the potential interaction of pesticides and ground water contamination (Chapter 4, page 51): "...Soil becomes poisoned as a result of heavy application of arsenical pesticides.... Rains then carry part of the arsenic into streams, rivers, reservoirs, as well as into the vast subterranean seas of ground water."

In addition to farm-generated pesticides, Carson also implicated chemicals from hazardous waste sites as ground water contaminants (Chapter 4, pages 40, 42, and 44):

> ...A variety of pollutants combine to produce deposits referred to as "gunk".... Holding ponds become chemical laboratories for the production of new chemicals.... Ground water becomes contami-

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16. ABSTRACT

An overview is presented of pesticide use and ground water contamination since the publication of Silent Spring. Progress in evaluation of this environmental problem is described, and some potential future issues are outlined.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

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> nated from this dump with the wastes traveling underground to nearby wells.... There is nothing probably more disturbing than the threat of widespread contamination of ground water.

Ground water contamination by pesticides, however, did not become an environmental issue until almost 2 decades after the publication of *Silent Spring* when widespread aquifer contamination by the pesticide aldicarb was found in the potato-growing region of Long Island, New York (*1*). This incident of ground water contamination was particularly significant because most area residents obtained their drinking water from privately owned shallow wells that tapped the aquifer.

An earlier example of contamination of ground water was reported in 1962 (*2*); 225 wells were found to contain compounds similar to phenoxy-type herbicides. These wells were thought to have been contaminated as a result of leakage from a nearby waste disposal basin.

These examples of drinking water contamination are among the reasons that ground water protection is one of today's major environmental issues. The need for ground water protection is compounded by the steady increase in the use of ground water for human consumption and for irrigation of farmland in semiarid and arid regions. In fact, withdrawal of ground water has tripled since 1950; the resource accounts for 25% of all fresh water used in the United States (*3*).

Current pesticide application technologies, land management practices, and pesticide properties also increase environmental concerns. New technologies that mix pesticides in irrigation water (chemigation) are used to apply agricultural chemicals to various crops. Conservation tillage, which leaves a protective crop residue on the soil, is used to reduce runoff and erosion, but it promotes the infiltration of pesticides into the soil profile. Soluble pesticides that partition (mix) into the water phase of the soil profile have replaced relatively insoluble chemicals.

The potential for aquifer contamination by leakage of chemicals, either disposed of or stored in landfills, lagoons, and holding ponds, is an additional environmental concern. Many such sites are found throughout the United States.

Ground water contamination, therefore, is among the most

complex issues currently facing environmental scientists and regulators. Because of its location beneath the water table, ground water presents especially difficult problems in detecting and monitoring contaminant levels and in evaluating the fate and effects of the pollutants. Remedial actions are difficult and expensive.

This chapter provides an overview of pesticide use and ground water contamination since the publication of *Silent Spring*, describes the progress in evaluation of this environmental problem, and projects some potential future issues that will have to be addressed.

Pesticide Leaching from Agricultural Fields

The vast majority of pesticides produced and used for agriculture when *Silent Spring* was published have either been discontinued because of efficacy problems or environmental concerns or restricted to specific nonagricultural uses. Any current direct investigation of ground water contaminated by these older discontinued pesticides that involved the monitoring of wells in agricultural areas would be difficult to interpret. Another means to evaluate past and present pesticide residues would be to conduct a literature search of reported ground water contamination. One such literature review, however, did not reveal appreciable contamination of ground water by pesticides produced in the past (2), partly because research emphasis has been on surface waters and nontarget organisms.

A solution would be to compare the relative potential for ground water contamination by pesticides from the past and pesticides currently used by developing a comparative methodology from known physicochemical properties. The objective would be to rank pesticides from past to present using a common reference that would indicate either a low or a high potential for ground water contamination based solely on the pesticide's mobility. (This approach would yield a conservative qualitative evaluation because transformation or decay would be ignored.) The methodology could be used in combination with current literature on pesticides in ground water to further evaluate the problem.

Description of the Problem

Pesticides can enter ground water from both nonpoint sources (e.g., an agricultural watershed) and point sources (e.g., a hazardous waste site). Nonpoint sources are characterized by highly variable loadings; rainfall dominates the timing and magnitude of pesticide infiltration into the ground water. Point sources are much less varied; the loadings are thought to be steady inputs into the ground water.

The potentially widespread nature of nonpoint source contamination makes remedial action difficult because it does not result in single streams that can be isolated and controlled, as can those that emanate from a point source. Prevention or reduction of future contamination must be based on understanding the relationships among chemical properties, soil system properties, and the climatic and agronomic variables that can combine to induce or inhibit pesticide leaching.

Many investigations (*4–8*) have shown that a pesticide's solubility in water, sorptive properties, chemical formulation, and soil persistence largely determine its leaching potential. Similarly, the important environmental and agronomic factors that determine a pesticide's leaching potential include soil properties, climatic conditions, crop type, and cropping practices. In short, elements of the hydrologic cycle interact with the chemical properties and characteristics of pesticides to transform and transport them within the unsaturated zone and into the ground water.

The most important characteristic of the hydrologic cycle that influences the migration of pesticides within the unsaturated zone is *recharge* (the flux of water that enters the water table). Recharge can be estimated for a unit of cross-sectional area of the land's surface by the *water balance equation*:

$$L + P = E + R_s + S + R \qquad (1)$$

where L is the hydraulic loading of man-made sources (e.g., irrigation), P is precipitation, E is evapotranspiration (loss of water from the soil by evaporation and by transpiration from growing plants), R_s is surface runoff, S is the change in storage, and R is recharge. All values are in centimeters per year.

The driving force that largely determines recharge is total precipitation, which varies considerably from region to region. Man-made inputs such as irrigation are generally confined to the West, where evapotranspiration demands normally exceed rainfall, and to parts of the Southeast. The influence of irrigation on total recharge is generally small because most irrigation is designed only to meet evapotranspiration demands; however, some practices such as flood irrigation and spraying to prevent frost damage can contribute significantly to local recharge. The storage capacity of the unsaturated zone generally remains constant, particularly when averaged over a year or longer. Therefore, its change can be effectively dropped from the equation.

Because most pesticides are applied on or just beneath the soil surface, the rainfall–infiltration–runoff process must be quantitatively described to evaluate recharge in the context of potential pesticide leaching to ground water. To accomplish this evaluation, the water balance equation is simplified (unless specific irrigation practices dictate differently) as follows

$$R + P - R_s - E \qquad (2)$$

The total annual recharge estimated from Equation 2 can vary from less than 10.0 to more than 90.0 cm/year for different regions of the United States and is different from year to year.

Interaction with this recharging water largely determines a pesticide's transport and fate characteristics. The sorptive properties of pesticides significantly affect their physical movement because they determine the distribution of the chemical between the solid and aqueous phases of the soil matrix. Pesticides distributed in the aqueous phase can be carried in the recharging water to ground water. The sorptive properties of nonpolar pesticides generally correlate well with the organic carbon content of soil.

The available water-holding capacity of soils at any particular time is affected by such properties as temperature, humidity, soil texture and structure, organic carbon content, and plant-crop characteristics. The amount of water that exceeds this available storage capacity (after correction for runoff and evapotranspiration) will infiltrate down through the soil profile

and eventually reach the ground water (unless it is intercepted by tile drains or impermeable layers above the water table). The *field capacity* of a soil, defined as the moisture content after gravity drainage has ceased, is less for sands and sandy loams than for clays and clay loams. The ability of pesticides to migrate with recharging water is greatest for soils with low water-holding potential. The *bulk density* of soils generally ranges from 1.0 to 2.0 g/cm^3; 1.25 to 1.75 g/cm^3 is common to sands and sandy loam soils (*9*).

The sorptive properties of pesticides and the water-holding and density characteristics of soils can be used to rank the relative mobility of pesticides with respect to water by estimating a *retardation factor*. The retardation factor provides a relative indicator of mobility and hence ground water contamination. Water has a retardation factor of 1.0. A pesticide with a retardation factor of 2.0 would possess mobility one-half that of water. The retardation factors of older pesticides are very high, so their leaching potential is very low. However, the retardation factors of older pesticides have decreased with time. For present-day pesticides, retardation factors can approach 1.0, so their leaching potential is high (i.e., the pesticides would move with the recharging water front through the soil).

Since *Silent Spring*'s publication, the leaching potential of most commonly used pesticides has increased. Most of this increase has occurred since 1970 with the advent of carbamate pesticides, which are very water soluble.

Specific Cases

A 1974 review of ground water contamination from pesticides and other chemicals reported the contamination of a shallow-bored well by DDT and toxaphene (*2*). It was discovered that pesticide-contaminated soil had been used as a backfill, and thus the contamination was caused by the movement of contaminated soil to the ground water instead of by the usual contaminated recharge-water pathway. In the same review, laboratory studies were identified in which several older organochlorine chemicals were leached with water in soil columns. The only pesticide found to leach was lindane.

Lindane has also been found in ground water in Israel (*10*). Lindane's estimated retardation factor was the lowest of the older pesticides evaluated. Additionally, the review indicated that the occurrence of ground water contamination resulting from agricultural fertilization was much more prevalent with heavy application of mobile forms of elements such as nitrogen, phosphorus, and chloride.

A 1984 review (*11*) found pesticide leaching from agricultural fields to be more widespread than in 1974. Pesticides currently used are more likely to contaminate ground water than pesticides used in the past. Several general observations can be drawn from the 1984 review:

- Contamination has been limited to shallow, unconfined aquifers consisting of porous sands (DBCP and EDB are exceptions).
- Contamination within the unconfined aquifer has been limited to near field wells (DBCP, EDB, and aldicarb are exceptions).
- Contamination levels found have been in the low parts-per-billion range.
- Contamination has been mainly observed for carbamate, triazine, and low molecular weight halogenated hydrocarbon classes of pesticides (aromatic acids are proposed to be included in this group).
- Contamination is most likely in agricultural areas that have nitrate contamination problems.
- Contamination does not seem to be limited to any one geographical region (pesticide residues have been found in ground water from New York to California).
- Contamination potential is high if the compound does not hydrolyze readily, has a low volatilization potential (Henry's law constant), has a low sorption potential, and possesses a first-order degradation rate in soil of at least 0.02 $days^{-1}$.

These results for pesticides differ substantially from those found for hazardous wastes. For example, concentrations of hazardous wastes in ground water were found in the hundreds of parts-per-million range, and migration was measured in kilometers rather than meters, as is typical in the near field scenario for pesticides used in agriculture. Several observations can be made concerning these vastly different results for agricultural pesticides:

- The source term (that is, the mass applied) to the land surface is much smaller for pesticides used in agriculture, typically 1.2–2.2 kilograms per hectare as compared to metric tonnes per hectare estimated for hazardous wastes.
- This applied mass is subjected to a variety of soil water processes such as sorption (retardation), transformation or decay, plant removal, and interaction with advection and diffusion-dispersion processes that are conducive to reducing the mass available for infiltration into ground water.
- Analytical capability has greatly increased for pesticides. Nanogram or picogram levels are now commonly identified, whereas a few years ago only milligram levels were obtainable.

Evaluation of Past and Present Pesticides

From our analysis of past and present pesticide use for agriculture, several conclusions can be drawn:

- Pesticide characteristics have changed from the nearly water-insoluble, strongly sorbed, nonmobile compounds of the past to more water-soluble, slightly sorbed, mobile compounds. Part of this change is a result of environmental problems (e.g., bioaccumulation) associated with past compounds; however, pest resistance has also played an important role.
- Ground water contamination by pesticides produced and used through the 1960s probably was not an environmental problem.

- Ground water contamination by pesticides currently produced and used is an environmental problem.
- Low-level residues of pesticides identified in ground water generally may not present acute toxicity problems, but chronic effects will likely be of concern (assuming the toxicity is known).
- Ground water contamination from pesticide use does not necessarily mean that drinking water supplies will be affected unless the ground water is the supply source. Privately owned shallow wells in unconfined aquifers are probably at greater risk than large municipal wells in deeper, confined aquifers.
- Ground water contamination by pesticides involves some risk (pesticides by definition create this risk) and probably will have to be evaluated carefully in view of this risk potential. Pesticides account for 20% of the total agricultural chemical market, and some 3.7×10^5 metric tons of chemicals involving approximately 600 active ingredients are currently applied to agricultural land (*11*).

Carson's prophetic view of the effects of pesticides on the environment contributed greatly to the rapid development of both regulatory and scientific aspects of pesticide evaluation. The regulation of pesticides can be traced back to 1903 when truth-in-labeling laws required products to be efficacious as to label claims. However, the first true pesticide law enacted was the 1947 Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). This law did not provide for any direct means of evaluating the environmental effects of pesticides; its emphasis was on product efficacy. Shortly after *Silent Spring* was published, scientists were coming to conclusions similar to Carson's, a situation that led to the first request for environmental fate-related data to be submitted for pesticides in 1970. A substantially modified FIFRA was created in 1972 that required indicator test data on efficacy, metabolism, formulation and product chemistry, fish and wildlife effects, toxicology, and environmental fate and transport mechanisms to be provided for each chemical submitted to the U.S. Environmental Protec-

tion Agency (EPA) for registration. FIFRA is one of only two congressional laws that require submission of environmentally related data for chemicals manufactured for commercial use.

The occurrence of potentially toxic pesticides in ground water has led to intensive efforts toward environmental risk assessment for chemicals. Ground water contamination from pesticides results from the interaction of the hydrologic cycle and pesticide transport and transformation properties and characteristics. Many different climatic, soil, crop, land management, and chemical variables are inherent in this interaction. *Mathematical models* are currently being used to integrate these variables into a methodology that can provide quantitative indications of the loadings of pesticides to ground water. These models incorporate and simulate the important features associated with pesticide leaching from agricultural fields, that is, quantitative representations of plant-soil-management practices, the hydrologic cycle, and chemical processes and reactions.

The use of models to generate time series data is an accepted technique to derive probability statements about hydrologic events. Similarly, pesticide fate and transport models have been used to estimate probabilities of environmental exposure expressed as frequency distributions of concentrations in surface waters (*12, 13*). Models that derive probability statements about the mass of pesticides that could contaminate ground water appear to be valuable tools in assigning relative risks to pesticide use.

Future Issues

Significant progress has been achieved in identifying and evaluating the important climatic conditions, soil properties, and chemical properties and characteristics that are conducive to contamination of ground water by pesticides. Agricultural practices are constantly changing, however, to increase the production of food for both American and world needs. Pesticide formulations will evolve to keep abreast of agricultural practices and the changes in pest characteristics.

The number of hectares of fertile productive farmland is decreasing as a result of the sale of farmland for commercial or residential land development and because of the loss of topsoil from erosion. The development and implementation of conservation tillage is being promoted as a means of reducing runoff and erosion losses from farmland. Conservation tillage increases the amount of water that infiltrates into the soil profile. Part of this increased infiltration may be added to the recharge term of the water balance equation. This increase in recharge could increase the contamination of ground water by soluble pesticides.

Conservation tillage has been demonstrated to reduce pesticide loss due to runoff and erosion (*14*). Unfortunately, there is a lack of monitoring data on pesticide migration to ground water from these practices. A recent model comparison study of conservation tillage (till plant) and conventional tillage (disk harrowing) using three representative pesticides on three agricultural fields indicated conservation tillage increased the potential for pesticide leaching in two of the three fields (*15*). The effect conservation tillage has on ground water quality clearly warrants further evaluation.

The use of irrigation for agriculture is increasing in some parts of the United States. Chemigation (mixing of pesticides in irrigation water) is being used increasingly to apply pesticides to crops. The use of water-soluble chemicals for chemigation where flood irrigation or chemigation followed by irrigation is used for frost protection may also enhance the migration of soluble pesticides to ground water. The effect of chemigation on ground water quality is also unknown and requires additional study.

Pesticides will continue to be developed in response to new agricultural practices and needs, changes in pest resistance, and technological advances in pesticide chemistry. The development of strategies for the protection of ground water and its beneficial uses must keep pace with this changing technology. Screening methodologies and mathematical models offer one potential cost-effective technique to develop, update, and evaluate such strategies.

Glossary

Advection The vertical movement of water.

Agronomy The branch of agriculture dealing with crop production.

Aquifer A water-bearing bed of permeable rock, sand, or gravel capable of yielding considerable quantities of water to wells or springs. A confined aquifer is one that is confined between two aquitards (confining beds). An unconfined aquifer is one in which the water table forms an upper boundary (not confined).

Hydrologic cycle The complex sequence of conditions through which water naturally passes from the atmosphere by precipitation on land or water surfaces and ultimately back into the atmosphere by evaporation and animal and plant transpiration.

Nonpolar pesticides Those that are electrically neutral; that is, they possess no charge.

Octanol–water partition coefficient A measure of a chemical's ability to dissolve in fat; the higher the coefficient, the higher the ability to dissolve in fat.

Qualitative evaluation An evaluation that reduces information from a general to a more particular or restricted form.

Tile drain A hollow unit made of clay buried underneath the soil for constructing a drain.

Time-series data Output from a mathematical model in terms of mass (grams or milligrams) or concentration per unit time (day, month, or year).

Transformation A change in composition or structure.

Unsaturated zone That part of the soil above the water table where soil is not saturated.

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